
DEVELOPMENT OF MODEL FOR THE ESTIMATION OF WEIGHTED ATMOSPHERIC MEAN TEMPERATURE IN BENUE STATE, NIGERIA

¹SUKAM, Y.M., ²ODO F.E. AND OGWUCHE E.¹

¹Department of SLT, NACEST Makurdi

²Department of Computer, NACEST Makurdi

*Corresponding Author: ymsukam@gmail.com

ABSTRACT

Weighted Atmospheric Mean Temperature (T_m) is the average mean temperature of precipitable water vapour in a given column of the atmosphere. Precipitable water vapour is the amount water present in a given column of the atmosphere. It is vital in weather forecasting and radio communication links. It forms the basis for understanding atmospheric dynamics; which is vital for wind tunneling in aircraft designs. Accurate measurement of T_m is central to the estimation of precipitable water vapour. In Benue State, a sub-Sahara region of West Africa, which lies between latitude $6.5 - 8.5^\circ\text{N}$ and longitude 7.47 and 10°E respectively, is driven by convective activities and the movement of the Inter-Tropical Discontinuity (ITD). In this region, Atmospheric stations equipped with radiosonde for direct measurement of T_m are very scarce and do not have wider coverage of data collection over time. Hence, it has become imperative to infer T_m from satellite data to develop models that would cover for the data gap. Using eleven-year monthly averaged data from Climate Monitoring Satellite Application Facility (CM-SAF), for eight stations in Benue State, an empirical model of the form $T_m = aT_s + c$ (where T_m is the weighted atmospheric mean temperature, T_s is the surface temperature and a, c are constants) were found to be the best model estimation of T_m for Benue State. The model was found to agree with other similar models found for other regions of the world and upon validation with in-situ (Radiosonde) measurements the model was found to have a MBE of 0.034K and RMSE 0.072K .

Keywords: Precipitable water vapour, Weighted Atmospheric Mean Temperature, Surface temperature, Benue State.

INTRODUCTION

Weighted atmospheric mean temperature T_m , known as water vapour vertically averaged temperature of the atmosphere is a major factor for retrieving Precipitable Water Vapour (PWV) in the atmosphere. It plays an important role in energy equilibrium, global atmospheric radiation and the hydrological cycle. Despite the small quantity of water vapour in the atmosphere, its influence cannot be under-estimated, as it is responsible for the formation of cloud which leads to different forms of precipitation such as hail, sleet, snow, rain and freezing rain.

Precipitable water vapour, which is a function of T_m is similar to but different from other forms of moisture content such as mixing ratio, dew point temperature and relative humidity which measures the relative amount of moisture content in a given volume of air. Succinctly, T_m is the amount of the actual volume of water or depth of liquid water that exists in a given vertical column of the atmosphere. Measurement of T_m according to Duan *et al.* (1996) and Song *et al.* (2003) is an important part of forecasting short-range rainstorm and Meiyu Season respectively. It is also used for improving weather prediction models (Kuo *et al.*, 1993 and Gutman *et al.*, 2003), for studying temporal distribution of daily discrepancies of PWV (Wu *et al.*, 2003), for observing serious weather phenomenon such as hail stone, strong wind, thunderstorm and hurricane (Choy *et al.*, 2011).

Measurements of meteorological parameters used for the estimation of T_m can be done in a variety of ways such as the use of radiosondes for direct measurements; this method uses onboard sensor to sense atmospheric parameters across different pressure layers of the atmosphere during flight. These types of instruments, due to high costs, are not readily available in West Africa, leading to the consequence of non-availability of continuous data for meteorological, climate and atmospheric applications. Weighted atmospheric mean temperature on the other hand, could also be estimated from data obtained at the routine surface meteorological stations through the use of wet/dry-bulb thermometers and the dew point hygrometer. This process has the advantage of being inexpensive coupled with the fact that data spanning through an extended period could be obtained. The major drawback of this method is that the estimate is only for a particular region as opposed to meteorological satellites which has wider coverage and thus readily available across the globe.

Additionally, Regions within Benue state equipped with radiosondes for direct measurement of T_m are very scarce and most time does not have continuous data. This challenge led researchers into developing appropriate models for the estimation of T_m . However, despite numerous models developed for the estimation of T_m across other regions (as stated in literatures; Ross and Rosenfeld, 1997; Bevis *et al.*, 1992, 1994; Raju *et al.*, 2007; Fernandez *et al.*, 2010; Musa *et al.*, 2011; Ning and Elgered, 2013; Lilong *et al.*, 2015; Cao *et al.*, 2008; Yanxin *et al.*, 2013; Wang *et al.*, 2012 among others), Models for the estimation of T_m for Benue state using satellite data has not been fully investigated. Hence it has become imperative to develop T_m for Benue State using satellite data; which has both spatial and temporal resolution.

METHODOLOGY

The Study Area

The study area used for this research work is Benue state. The state is located in the sub-tropics within latitude 6.5 to 8.5 °N; and longitude 7.47 to 10 °E. Benue State experiences two distinct seasons, the wet/rainy season and the dry/summer season. The rainy season lasts from

Table 1: Details of locations from which satellite and Radiosonde data were obtained for the development and validation of the models

Stations	Latitude	Longitude	Data Type	Period of data
Apa	8.46 ⁰ N	7.91 ⁰ E	Satellite	2011-2022
Gwer	7.41 ⁰ N	8.35 ⁰ E	Satellite	2011-2022
Ado	7.79 ⁰ N	7.76 ⁰ E	Satellite	2011-2022
Gboko Katsina-Ala	7.36 ⁰ N	9.00 ⁰ E	Satellite	2011-2022
Oju	7.16 ⁰ N	9.28 ⁰ E	Satellite	2011-2022
Kwande	6.89 ⁰ N	8.35 ⁰ E	Satellite	2011-2022
Makurdi	6.91 ⁰ N	9.45 ⁰ E	Satellite	2011-2022
	7.73 ⁰ N	8.53 ⁰ E	Radiosonde	2011-2022

Data Analysis

The data used for the development of the model were monthly average of specific humidity, q_m (g/kg) and ambient temperature T (K), across six (6) different pressure levels of the atmosphere (level1 = 200 hpa; level2 = 300 hpa; level3 = 500 hpa; level4 = 700 hpa; level5 = 850 hpa and level6 (surface) = 1000 hpa). The data which spanned through the solar cycle (2011 to 2022) were obtained from the archive of the Climate Monitoring Satellite Application Facility (CM-SAF) at https://www.cmsaf.eu/EN/Home/home_node.html. The data which came in the form of NetCDF file was categorized into stations based on their longitude and latitude using the Panoply open source software (ver 4.3.1). Python Application (Jupyter notebook) was used for data extraction and preparation. The CM SAF is an integrated part of the European Meteorological Satellites (EUMETSAT) which generates, archive and distribute high quality satellite-derived products of the atmosphere.

The specific humidity q_m , was converted to vapour pressure e , using Eqn. 1 which was then used to estimate T_m as shown in Eqn. 5.

$$e = \frac{rp}{r+0.622} \quad (1)$$

where r is specific humidity (g/kg), p is atmospheric pressure (hpa) and e is the vapour pressure (in hpa).

In order to obtain T_m , Davis *et al.* (1985) defined and approximated T_m as

$$T_m = \frac{\int \frac{P_v}{T} dz}{\int \frac{P_v}{T^2} dz} \approx \frac{\sum_{i=1}^N \frac{P_{vi}}{T_i} \Delta z_i}{\sum_{i=1}^N \frac{P_{vi}}{T_i^2} \Delta z_i} \quad (3)$$

where P_v , T , and z are as defined in Eqn. 1.4

The integration in equation (3) can be discretized into sums of contributions from successive layers.

Hence:

$$T_m = \frac{\int_h^{\infty} \frac{e}{T} Z_w^{-1} dh}{\int_h^{\infty} \frac{e}{T^2} Z_w^{-1} dh} = \frac{\sum_i^n \left(\frac{e_i}{T_i} \right) \Delta S_i}{\sum_i^n \left(\frac{e_i}{T_i^2} \right) \Delta S_i} \quad (4)$$

where $\overline{\left(\frac{e_i}{T_i} \right)} = \left[\frac{\frac{e_i}{T_i} + \frac{e_{i-1}}{T_{i-1}}}{2} \right]$, $\overline{\left(\frac{e_i}{T_i^2} \right)} = \left[\frac{\frac{e_i}{T_i^2} + \frac{e_{i-1}}{T_{i-1}^2}}{2} \right]$,

ΔS_i is thickness of the atmosphere at the i th layer and e_i and T_i are the water vapor pressure and temperature at the top of the atmosphere at the i th layer, respectively. e_{i-1} and T_{i-1} are water vapor pressure and temperature at the bottom of the atmosphere at the i th layer, respectively, and n is the number of layers. Thus, by using 11 years Satellite data profiles, of monthly averages of vapor pressure and ambient temperature collected over 8 different locations in Benue state, Nigeria, T_m , can be estimated by integrating the vertical profiles of e and T . Since the linear regression model for estimating T_m proposed by Bevis *et al.* (1992) (which is also adopted in this study) varies with space, time and weather conditions. It is also necessary to generate a suitable model for estimating T_m peculiar to Benue by adjusting the constants a and b as stated in Eqn. 5. Consequently, the estimated weighted atmospheric mean temperature for Benue (from the satellite data) was plotted against surface temperature. The observed trend of the distribution was then fitted with the empirical model of the form in Eqn. 5

$$T_m = aT_s + b. \quad (5)$$

For the validation of the model, radiosonde data was used. Radiosonde is an in-situ battery powered meteorological instrument that is borne on weather balloons and flown vertically upward across different layers of the atmosphere (Leckner, 1978). It is meant to measure atmospheric parameters such as temperature, relative humidity, pressure, dew point temperature among others as it journeyed through the different layers of the atmosphere. In this case, monthly mean ambient temperature T ($^{\circ}\text{C}$) and dew point temperature T_d ($^{\circ}\text{C}$) across six different pressure levels (level 1 = 200 hpa; level 2 = 300 hpa; level 3 = 500 hpa; level 4 = 700 hpa; level 5 = 850 hpa and level 6 (surface) = 1000 hpa) of the atmosphere were used. The validation of the model was carried out in Makurdi. The data employed were collected in-situ. The data which spanned through the period 2023-2024 for Makurdi was used to estimate vapour pressure, e from the dew point temperature, and thus:

$$e = 6.11 \times 10^{\left(\frac{7.5 \times T_d}{237.3 + T_d} \right)} \quad (2)$$

where T_d is dew point temperature (in $^{\circ}\text{C}$) and e is vapour pressure (in hpa).

Then T_m for the in-situ measurement was obtained using Eqns. 4 and 5.

RESULTS AND DISCUSSIONS

Development of the Model

The plot of weighted atmospheric mean temperature T_m , against surface temperature T_s , for Benue State using satellite data is as shown in Figure 2. The plot was observed to have a linear distribution and hence a linear model was fitted to the distribution. The coefficient of determination R^2 , of the linear fit was found to be 0.8962 while the coefficient of regression a and b , for the linear model is as given in Table 2. The model obtained is of the form $T_m = aT_s + b$. When this model was compared with that of the entire globe obtained using radiosonde data, a MBE and RMSE of 0.034K 0.072K respectively was observed. This signifies a good correlation hence estimating closely the model obtained for Benue using satellite data; implying the satellite model could also be used in the absence of measured data. It was also observed that T_m (which is a function of water vapour in the atmosphere) relates directly to surface temperature, which is in agreement with the results obtained by Mendes *et al.* (2000) and Raju *et al.* (2007) who worked on the estimation of T_m from radiosonde data and observed that T_m relates directly to T_s across the region of Germany and the Indian sub-continent respectively. The plot of weighted atmospheric mean temperature as a function of surface temperature for the development of the model is as shown in Figure 2. The plot shows a coefficient of determination of 0.8962 and the constant a and b , which are peculiar to Benue state as 0.8236 and 46.49 respectively - as shown in Table 2.

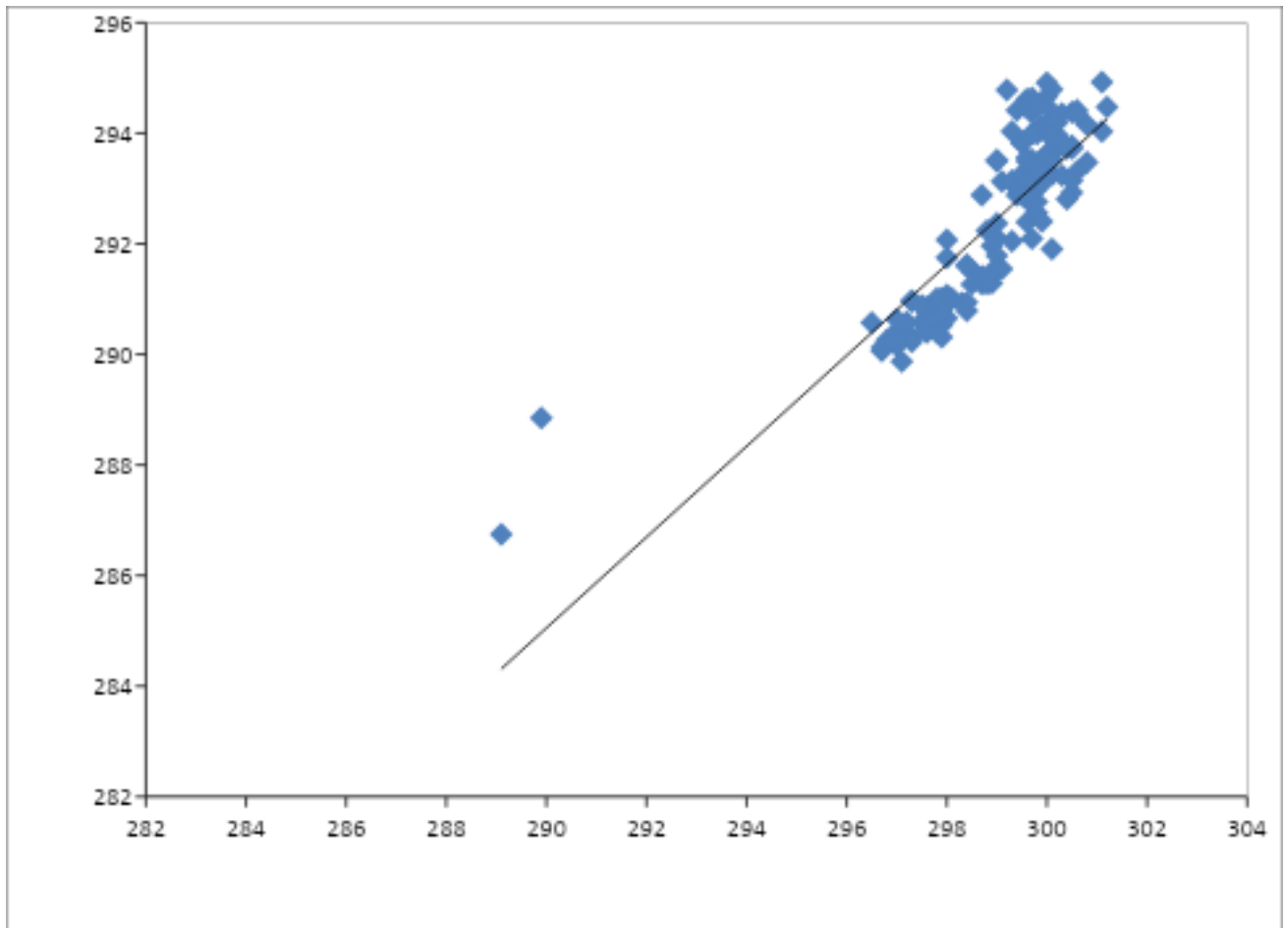


Figure 2: Weighted Atmospheric Mean Temperature T_m (K) as a function of Surface Temperature T_s (K) for Benue State

Table 2: Statistics of Weighted Atmospheric Mean Temperature for Benue State

Models	Empirical Model		Coefficient of Determination R ²
	$T_m = aT_s + b$		
	a	b	
T_{m_SB}	0.8236	46.49	0.8962

NOTE: T_m => Weighted Atmospheric Mean Temperature, T_s => Surface Temperature

Consequently, it was observed that the values of T_m obtained from the satellite model over estimated a little above the one obtained for the entire globe. Unlike the radiosonde instruments which are in-situ, the over estimation observed by the satellite model could be ascribed to the refraction of satellite signals as they travel through different pressure layers of the atmosphere which could affect its values. In line with the foregoing, Schueler *et al.* (2001) obtained a global model for the estimation of T_m using radiosonde data. The model was observed to have a lower intercept when compared with the one obtained for Benue State from satellite data. This discrepancy was attributed to location, the location of Benue state (Tropics), is predominantly covered by land masses; which is responsible for emitting infrared radiations. Implying that, the value of T_m depends is site dependent and vary seasonally.

Additionally, the lower value of the intercept observed from the global model could be ascribed to the fact that the earth is predominantly covered by water bodies. Unlike the earth crust, water molecules do not have the tendency to convert solar incident radiation to infrared thus resulting to a lower intercept at 0 °C. The results obtained when compared with the results obtained by Bevis *et al.* (1992) who worked on the estimation of T_m for the United States, observed that T_m varies geographically across the United States; which is also in agreement with the results obtained in this work. However, the results obtained herein and the results obtained by Isioye *et al.* (2016) follow the same pattern of distribution, the over-estimation of T_m observed over Benue State could be ascribed to the amount of moisture in the atmosphere (tropics), thereby resulting to higher ambient temperature than the united states.

Validation of the Model

The validation of the satellite model obtained for the estimation of T_m for Benue State was performed in Makurdi. Upon validation, it was observed that the satellite data follow closely (with minimal error) the in-situ data as seen from Figure 3. From the statistical analysis in Table 3, the MBE and RMSE between the satellite model for Benue State (T_{m_SB}) and in-situ measure (T_{m_RB}) is 0.034K and 0.072K respectively while between the T_{m_SB} and Global model (T_{m_RG}) is 0.798K and 0.1579K respectively. Signifying T_{m_SB} indicated a minimal error in estimating T_m compared with the T_{m_RG} hence; T_{m_SB} could be employed in estimating T_m for Benue State in the absence of measured data. Additionally, the satellite model was found to predict closely the radiosonde data with the index of agreement of 0.791 upon validation at Makurdi. This result is in agreement with the results obtained by Falaiye *et al.* (2020); who worked on the seasonality of T_m in West Africa and observed that T_m is site dependent and vary with the moisture content of the atmosphere.

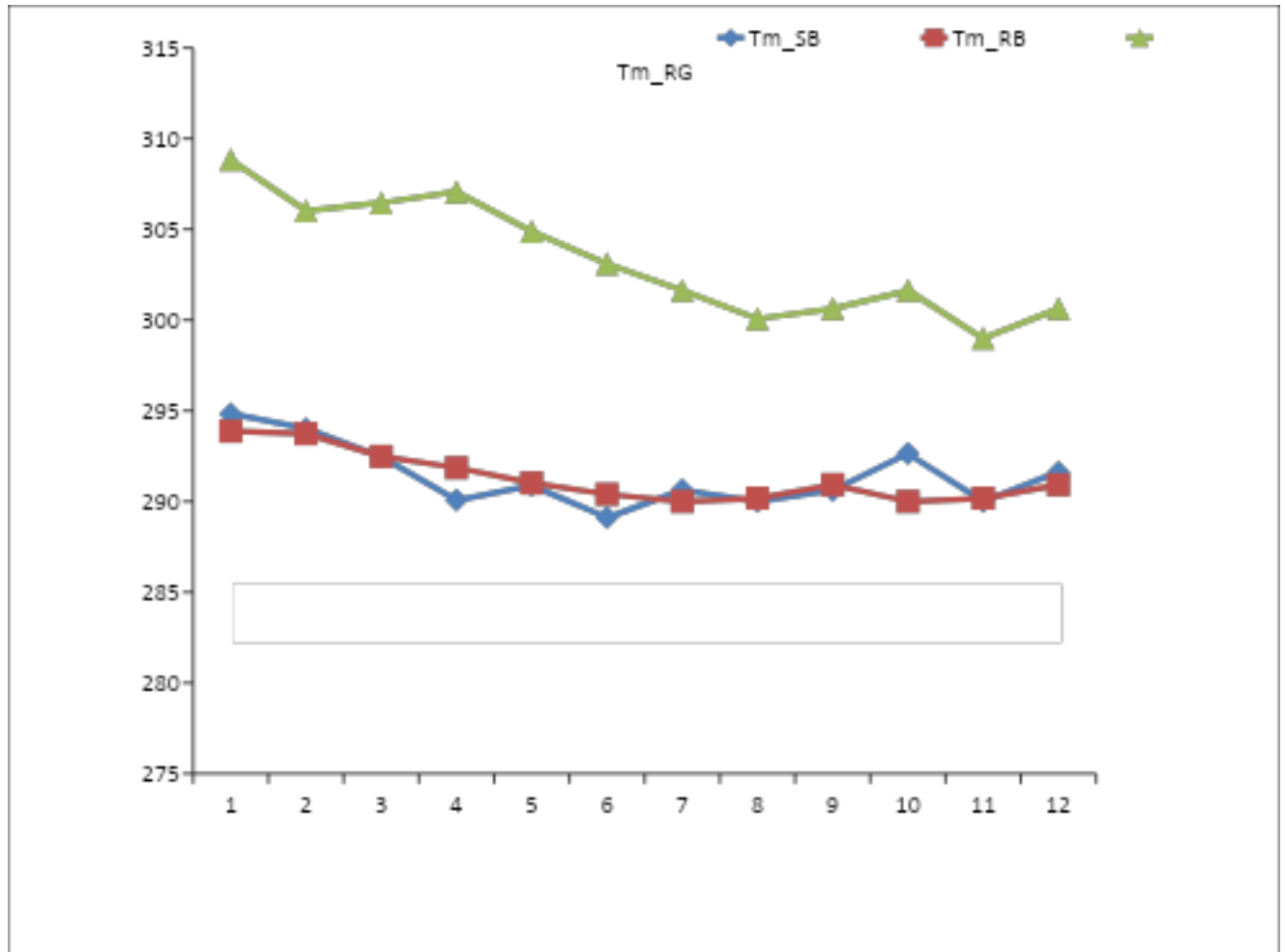


Figure 3: Time series plot for the Validation of T_m obtained for Benue State at Makurdi from July 2023 to August 2024.

Table 3: Summary of Statistical Analysis for the Validation of Weighted Atmospheric Mean Temperature T_m (K) obtained from Satellite and Radiosonde data at Makurdi.

MODELS	MBE(K)	RMSE(K)
T_{m_SB} and T_{m_RG}	0.798K	0.1579K
T_{m_SB} and T_{m_RB}	0.034K	0.072K

CONCLUSION

In this work, a suitable empirical model relating the weighted atmospheric mean temperature (T_m) to surface temperature (T_s) was found for Benue, Nigeria. The model was found to compare well with similar model obtained for the entire globe. Upon validation, it was observed that the MBE and RMSE between the satellite model (T_{m_SB}) and in-situ measure (T_{m_RB}) was 0.034K and 0.072K respectively while between the T_{m_SB} and Global model (T_{m_RG}) was 0.798K and 0.1579K respectively. This signifies that T_{m_SB} predicted closely the in-situ measurement, implying it could be used in estimating T_m for the region of Makurdi.

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